

# A Study of the Mechanism of Pressure Wave Distortion by Arterial Walls Using an Electrical Analog

By HOMER R. WARNER, M.D., PH.D.

The large arteries may be expected to respond to a central pulse wave as a resonant system and the pressure pulse can be resolved into a series of pure sinusoidal waves. Therefore, a frequency filter network was designed which could duplicate the resonant frequency and damping coefficient of a segment of artery by proper adjustment of the circuit constants. Data are presented which support the concept that much of the distortion of a pressure wave in its transmission down an artery can be explained in terms of a resonant frequency and damping coefficient, and that these variables in turn are dependent upon physical properties of the segment of artery transmitting the wave.

THE distortion of the arterial pressure wave as it travels peripherally has been the subject of much study and speculation by physiologists since it was first accurately demonstrated by Otto Frank.<sup>1</sup> He observed that the peak pressure in femoral artery of a dog was higher than in the subclavian and that its contour resembled the contour of the central pulse recorded with a low frequency manometer. Although he and several subsequent workers have attempted to explain this on the basis of wave reflections,<sup>2, 3</sup> more recent work has cast considerable doubt on this explanation.<sup>4-7</sup>

Since large arteries are elastic structures and are being stretched by a periodic force, they might be expected to respond as a "resonant system"; that is, pressure waves of certain frequencies might be amplified as they are transmitted down the artery while those of other frequencies lose amplitude in the process. Since a periodic function such as a pressure pulse can be resolved into a series of pure sinusoidal waves of frequencies which are multiples of the basic frequency by Fourier analysis, the arterial segment can be looked upon as being driven simultaneously by sine waves of all the component frequencies. It follows that if such an analysis were performed on the pres-

sure waves entering and leaving a segment of artery, a frequency response curve or transfer function could be obtained for that arterial segment by plotting the ratio of the output to the input amplitude coefficients as a function of frequency.

The transfer function of a system with one-degree of freedom can be completely characterized by two constants, the resonant frequency,  $f_n$ , and the damping ratio,  $C/C_c$ . Data will be presented which show that certain large arteries of dog and man have pressure wave transfer functions resembling such a simple system. A means of readily obtaining such data on a segment of artery using an electric analog will also be illustrated.

## METHODS

Observations were made on normal adult men and women and on mongrel dogs. Only local anesthesia was given the human beings while dogs were anesthetized with intravenous Nembutal (30 mg./Kg.).

The central arterial pressure was obtained by means of a small Peterson-type<sup>8</sup> arterial catheter\* advanced into the aortic arch through a thin walled 18 gage needle in the right femoral artery.<sup>9</sup> The proximal end of the catheter was attached to a strain gage manometer (Statham model P-23 D). Left radial or brachial and left femoral pressures were obtained through 20 gage needles attached to systems utilizing similar strain gage transducers. The frequency response of the catheter-manometer-galvanometer systems used is claimed to be adequate for the purpose of the present study.<sup>10, 11</sup>

A low frequency filter network† was designed

---

From the Department of Physiology, Latter Day Saints Hospital and University of Utah, Salt Lake City, Utah.

Supported by a grant from the Utah Heart Association and Grant H 2073, U. S. Public Health Service.

Received for publication September 10, 1956.

---

\* Obtained from Mr. Albert Afford, Barrington, New Jersey.

† Built by Engineering Specialty Co. (ENSCO

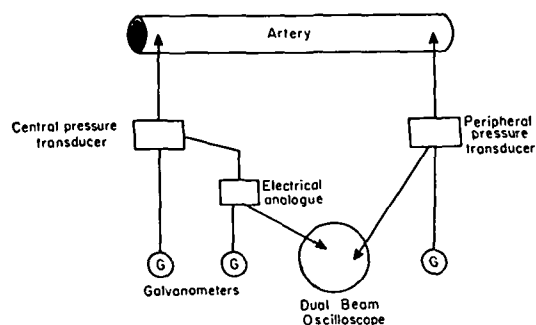


FIG. 1. Schema showing experimental arrangement for using an electric analog to distort the electric wave form coming from the central pressure transducer in the same way as the segment of artery is distorting the central pressure wave form.

equivalent to a series resonant RCL circuit whose input is across the elements in series and whose output is the voltage across the capacitor. The resonant frequency of the circuit can be varied from 0.5 to 15 cycles per second. Damping can be varied independently. The output voltage from the transducer recording the central pulse is fed into the filter circuit, the output of which is viewed on a high-sensitivity dual-beam oscilloscope† along with the output pulse from the segment of artery under study (radial or femoral) (fig. 1). The resonant frequency and damping of the circuit are then varied until its output most closely matches the output pulse from the artery. Both outputs are fed directly to optimally damped galvanometers (Heiland type 40-1000) and recorded photographically at a chart speed of 75 mm./sec.

In the early stages of the study, Fourier analysis of the central and peripheral pressure pulses was carried out using a 24 point graphic method.<sup>12</sup> Data obtained using this tedious and rather crude method provided the stimulus for construction of the electric analog described above. The resonant frequency and damping coefficient are now obtained directly from the dial settings on the analog used for matching the pulse during the experiment. These settings are calibrated using a low frequency oscillator.§

### RESULTS

In figure 2 is shown a direct recording of a radial artery pressure pulse. Below this are the harmonics drawn to scale as obtained by the rather crude graphic method. The dashed line in the upper curve is the radial pressure pulse

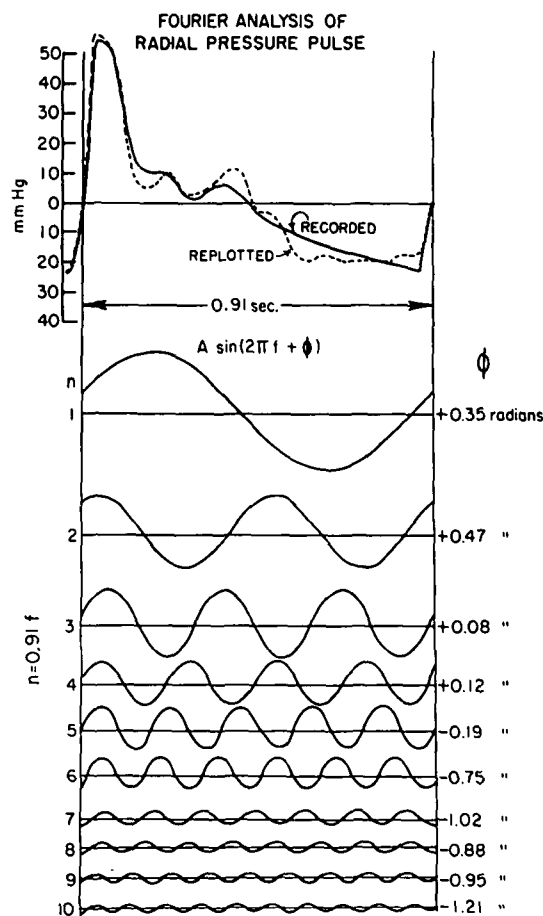


FIG. 2. Recorded radial artery pressure wave with first 10 frequency components drawn to scale.  $f$ , Frequency in cycles per second;  $\phi$ , phase angle in radians.

resynthesized by adding the component sine waves.

An example of the results obtained by performing a Fourier analysis on simultaneous central and peripheral arterial pressure pulses recorded from a normal 25 year old man are shown in figure 3. The absolute values of the amplitude coefficients are plotted as a function of frequency in the solid lines. It can be seen that the amplitude falls rapidly with increasing frequency, reaching a value of less than 0.1 of the 1 c.p.s. amplitude at 7 c.p.s. In contrast to this, it will be seen that the ratio of output (peripheral) amplitude to input (central) amplitude starts at a value near unity and goes through a maximum at about 3.5 c.p.s.

The general contour of transfer function

Model LFF-1) 3100 Eldredge St., Salt Lake City, Utah.

† Dumont type 333.

§ ENSCO Model LFO-1.

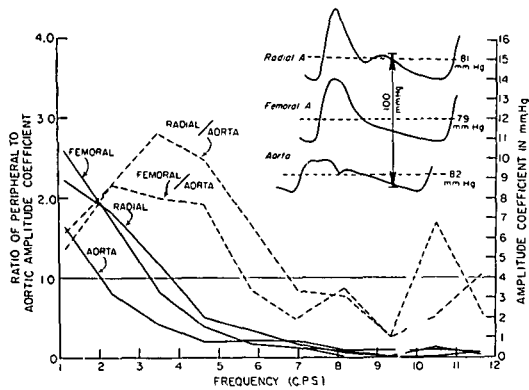


FIG. 3. Three simultaneously recorded pressure waves subjected to Fourier analysis (upper right). The amplitude coefficients are plotted as a function of frequency (solid lines) and the ratio of output/input as broken lines.

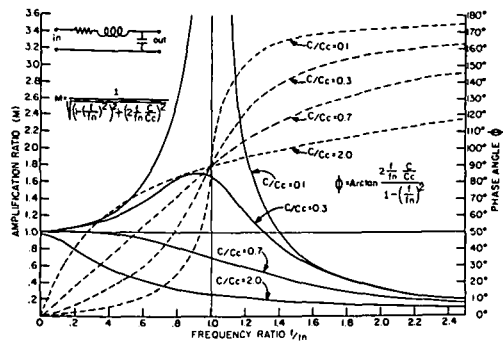


FIG. 4. The two equations describe the amplification ( $M$ ) and difference in phase angle ( $\phi$ ) between the input voltage and the voltage across the capacitor in the circuit shown. Note that these are completely described in terms of  $f_n$  and  $C/C_c$ . The curves illustrate particular values for  $M$  (solid) and  $\phi$  (broken).

curves such as these suggested the possibility of simulating the arterial bed using an electric analog. In figure 4 is shown a plot of magnification factor and difference in phase angle between input and output as a function of frequency for the series resonant circuit depicted. Such curves are completely defined in terms of resonant frequency,  $f_n$ , and the ratio of damping to critical damping,  $C/C_c$ .

The output of the transducer recording the central arterial pressure wave form was fed into a circuit equivalent to the one shown. It was found that by arriving at the correct circuit values through the method of trial and error, the circuit output could be made to match the

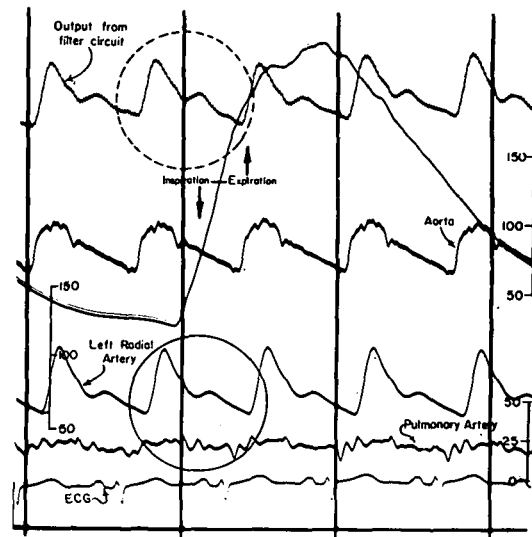


FIG. 5. Direct recordings of aortic and radial artery pressure from a normal man. The top trace is the output from the aortic pressure transducer after it has passed through the filter circuit. Ignore other records.

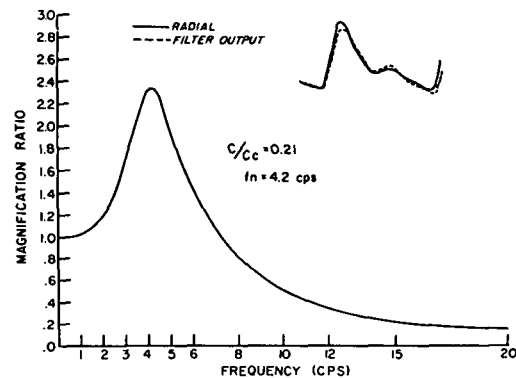


FIG. 6. Transfer function (output/input) of filter circuit obtained by direct calibration using an oscillator at the end of the experiment with the circuit constants set where they were when the record shown in figure 5 was taken. The extent to which the circuit is a true analog of this segment of artery (aorta to radial) may be judged by the similarity of the two wave-forms retraced from figure 5 and superimposed for ease of comparison.

wave form of the peripheral pulse. In other words, the circuit was altering the electric wave form in the same fashion as the segment of artery was altering the pressure wave form.

In figure 5 is shown a direct recording, obtained from a normal man, of pressure in the aortic arch and radial artery, and aortic pres-

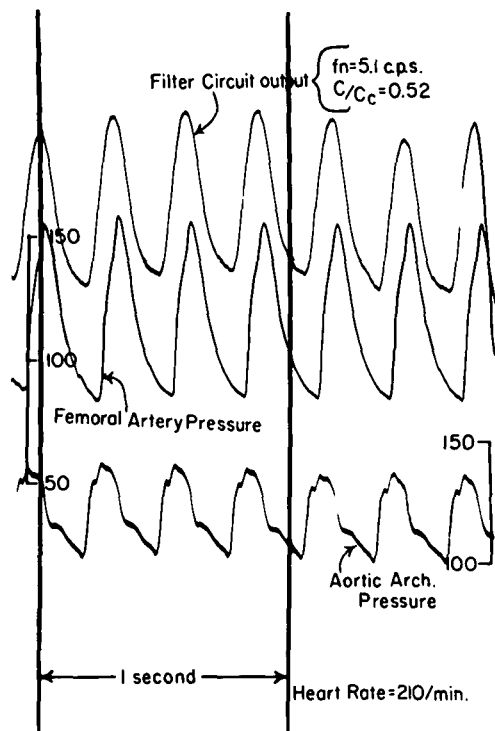


FIG. 7. Direct recording of aortic and femoral artery pressure from a dog and of the output from the aortic transducer after passing through the filter circuit.

sure after passing through the electric analog. In figure 6 is shown the frequency response curve of the filter circuit with its values set where they were when the record in figure 5 was taken. The extent to which the circuit is a true analog of the segment of artery is judged by the similarity of the two output wave forms. The encircled beats of figure 5 are retraced on figure 6 for ease of comparison.

In figure 7 is shown a direct recording of pressure from the aorta and femoral artery of a dog. Also shown is the aortic pressure wave after having passed through the electric analog. These examples serve to illustrate the principle involved. Although many variations in wave form of the peripheral pulse have been observed, a good match can, in our experience to date, be obtained using the analog presented.

That the transfer function of a segment of artery actually does vary with the physical properties of the arterial wall is demonstrated by the experiment illustrated in figures 8 and 9. Using two arterial catheters, pressure was

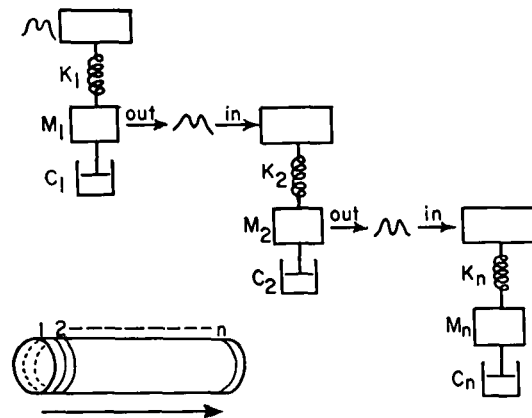


FIG. 8. Direct recording of pressure at two points in the aorta of an open-chest dog. Note the alteration in wave form that occurs and the values for  $f_n$  and  $C/C_c$  necessary to match the filter circuit output to wave form coming out at the level of the diaphragm. The absolute amplitude of the filter circuit output is arbitrary.

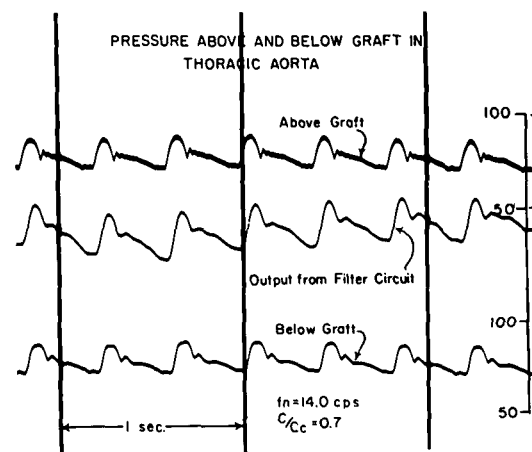


FIG. 9. Recording of pressure at same two sites as figure 8 after replacement of segment of aorta with Ivalon graft. Filter circuit does not perform satisfactorily at this high frequency. Note how the pressure wave is now transmitted almost undistorted.

recorded entering and leaving a 15 cm. segment of the thoracic aorta in an open-chest dog. The resonant frequency of the segment was found to be 4.4 c.p.s. and  $C/C_c$  was 0.28. An arterial graft of the same dimensions as the removed segment of artery was then inserted and the new values for  $f_n$  and  $C/C_c$  were found to be 14.0 c.p.s. and 0.7 respectively. The Ivalon graft, by direct measurement, was found to be only  $\frac{1}{3}$  as distensible as the artery in the

range of pressures encountered in the experiment.

### DISCUSSION

The results presented support the notion that large arteries behave as a resonant system. What does this mean in terms of the mechanism of energy transfer or pressure transmission by the artery? The model in figure 10 illustrates the concept proposed.

Let the hollow elastic cylinder represent a segment of artery, consisting of  $n$  smaller segments. The potential energy or pressure in each small segment will depend upon the energy transmitted to it from the previous segment and the extent to which it accepts pressure or energy variations of the incoming frequency. This segment in turn transfers its pressure to the subsequent section.

Each small segment might be likened to a mass ( $M$ ) suspended from a base by a spring whose constant ( $K$ ) is defined as the static force required to produce a unit change in length; ( $C$ ) is the proportionality constant between the frictional force and the velocity of stretching. In such a system the magnitude of variations in displacement or potential energy of the mass in response to a given displacement of the base will be frequency dependent in the same fashion as the electric analog already described. The resonant frequency and damping ratio for each component are determined by the following equations:

$$f_n = \frac{1}{2\pi} \sqrt{K/M} \quad C/C_c = C/\sqrt{4KM}$$

For a system of considerable length to react in the simple fashion that the over-all transfer function implies, each of its component parts must do one of two things: (1) be optimally damped with a flat transfer function over the range of frequencies whose amplitudes are significant in the pulse entering that segment or, (2) if significantly underdamped, have a resonant frequency close to all the other underdamped segments in the system. Data on multiple segments of aorta tending to support this concept have been obtained. These data will be presented in a subsequent paper concerned with a systematic study of the variations in  $f_n$  and  $C/C_c$ . It is believed that a "lumped"

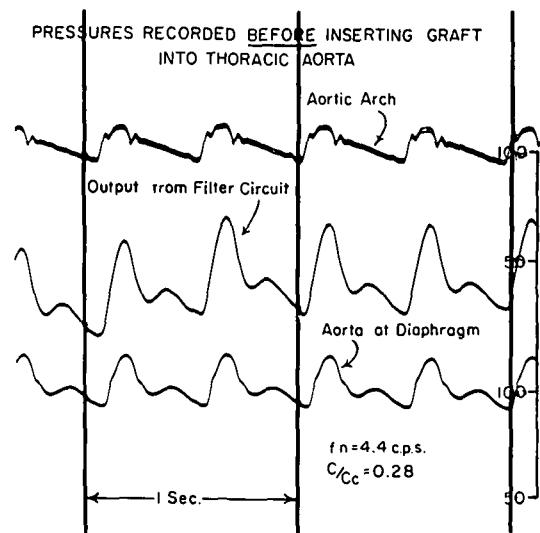


FIG. 10. Mechanical analog employed to explain resonance phenomena in an artery.

value of  $f_n$  and  $C/C_c$  for a large segment of artery will reveal useful information regarding the elasticity, "effective" mass and internal friction forces involved in the stretching process.

Otto Frank's<sup>1</sup> early suggestion that the femoral pressure wave form resembles the central pressure recorded with a low frequency manometer may now be interpreted on the basis of the findings reported. One need only look upon the segment of artery lying between the aortic arch and peripheral recording site as part of a line transmitting the pulse wave to the pressure transducer to understand how the amplitude and phase distortion required to bring about the observed alteration in wave form could be accomplished. Lawton,<sup>13</sup> working with isolated strips of dog aorta, reports a value for resonant frequency of 4.5 c.p.s. Although this is similar to our values, comparison is difficult since he failed to report the weight used in arriving at this value for resonant frequency. His calculated values for  $C/C_c$  are much smaller than we encountered.

### SUMMARY

A theory to explain the variation in contour of the central arterial pressure wave as it is transmitted peripherally is presented. From Fourier analysis of simultaneous central and

peripheral pressure waves it has been found that pressure transmission by a segment of artery is frequency dependent. The shape of the frequency response curve suggested an electric analog. This can be made to distort the electric wave form from the transducer recording central arterial pressure in the same manner that the artery distorts the pressure wave form and is used to obtain directly the frequency response curve of the artery.

A theory is presented which explains much of the pressure wave distortion by the artery in terms of variations in "effective mass," elasticity and internal friction in the wall of the artery.

#### ACKNOWLEDGMENT

The author gratefully acknowledges the technical assistance of Mr. Arthur Wilkinson in the design and construction of much of the apparatus, and of Mrs. Sylvia Quick in the preparation of the manuscript.

#### SUMMARIO IN INTERLINGUA

Es presentate un theoria que explica le variationes de contorno in le unda del pression arterial central durante su transmission al peripheria. Per medio del analyse harmonic de simultanee undas de pression central e peripheric, il esseva constatate que le transmission del pression per un segmento de arteria depende del frequentia. Le forma del curva de responsas de frequentia suggere un analogo electric. Iste analogo—que pote esser inducite a distorquer le forma del unda electric veniente ab le transductor usate pro registrar le central pression arterial, in le mesme maniera in que le arteria distorque le forma del unda de pression—es empleate pro obtener directemente le curva de responsas de frequentia del arteria.

Es presentate un theoria que explica un grande parte del distorsion effectuate in le unda de pression per le arteria super le base de

"massa effective," elasticitate, e friction interne in le pariete del arteria.

#### REFERENCES

- <sup>1</sup> FRANK, O.: Der Puls in den Arterien. *Ztschr. Biol.* **46**: 441, 1905.
- <sup>2</sup> WIGGERS, C. J.: *Pressure Pulses in the Cardiovascular System*. London and New York, Longmans Green, 1928.
- <sup>3</sup> HAMILTON, W. F., AND DOW, P.: An experimental study of the standing waves in the pulse propagation through the aorta. *Am. J. Physiol.* **125**: 48, 1939.
- <sup>4</sup> REMINGTON, J. W., AND WOOD, E. H.: Standing waves in human arterial pulses. *Am. J. Physiol.* **183**: 654, 1955.
- <sup>5</sup> PETERSON, L. H., AND GERST, P. H.: Significance of reflected waves within the arterial system. *Fed. Proc.* **51**: 144, 1956.
- <sup>6</sup> WARNER, H. R.: Synthesis of central arterial pressure-pulse contour from recording of radial artery pressure in man. *Am. J. Physiol.* **183**: 670, 1955.
- <sup>7</sup> KROCKER, E. J., AND WOOD, E. H.: Comparison of simultaneously recorded central and peripheral arterial pressure pulses during rest, exercise, and tilted position in man. *Circulation Research* **3**: 623, 1955.
- <sup>8</sup> PETERSON, L. H., DRIPPS, R. D., AND RISMAN, G. C.: A method for recording the arterial pressure pulse and blood pressure in man. *Am. Heart J.* **37**: 771, 1949.
- <sup>9</sup> WARNER, H. R., SWANN, H. J. C., CONNOLLY, D. C., TOMPKINS, R. G., AND WOOD, E. H.: Quantitation of beat-to-beat changes in stroke volume from the aortic pulse contour in man. *J. Appl. Physiol.* **5**: 495, 1953.
- <sup>10</sup> WOOD, E. H., LEUSEN, I. R., AND WARNER, H. R.: Comparison of aortic pressure pulses recorded by strain-gauge and capacitance manometer-catheter systems in man. *Am. J. Physiol.* **171**: 780, 1952.
- <sup>11</sup> —: Special instrumentation problems encountered in physiological research concerning the heart and circulation in man. *Science* **112**: 707, 1950.
- <sup>12</sup> The Royal Signals Handbook of Line Communication vol. I, p. 106–111.
- <sup>13</sup> LAWTON, R. W.: Measurements on the elasticity and damping of isolated aortic strips of the dog. *Circulation Research* **3**: 403, 1955.